

NASA/TM—2006-214395



Thin Film Physical Sensor Instrumentation Research and Development at NASA Glenn Research Center

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September 2006

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Prepared for the
52nd International Instrumentation Symposium
cosponsored by the ISA Aerospace, Test Measurement
and Process Measurement and Control Divisions
Cleveland, Ohio, May 7–11, 2006

National Aeronautics and
Space Administration

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Acknowledgments

We gratefully acknowledge the support of the staff of the NASA Glenn Research Center Test Facilities Operation, Maintenance, and Engineering (TFOME) organization for making this research and development effort possible. We also acknowledge the efforts of past researchers who established the reputation of NASA Glenn as a world-class center in thin film sensor research and development. We give our thanks to Dr. Ali Sayir of Case Western Reserve University (Cleveland, Ohio) and Dr. Otto Gregory of the University of Rhode Island (Kingston, Rhode Island) as collaborators on the ceramic thin film sensor projects. The work presented here was funded by a variety of programs of NASA's Aeronautics Research Missions Directorate. This overview was sponsored by the Prop21 project of NASA's Vehicle Systems Program.

This report contains preliminary findings,
subject to revision as analysis proceeds.

This work was sponsored by the Fundamental Aeronautics Program
at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by technical management.

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Abstract

A range of thin film sensor technology has been demonstrated enabling measurement of multiple parameters either individually or in sensor arrays including temperature, strain, heat flux, and flow. Multiple techniques exist for refractory thin film fabrication, fabrication and integration on complex surfaces, and multilayered thin film insulation. Leveraging expertise in thin films and high temperature materials, investigations for the applications of thin film ceramic sensors has begun. The current challenges of instrumentation technology are to further develop systems packaging and component testing of specialized sensors, further develop instrumentation techniques on complex surfaces, improve sensor durability, and to address needs for extreme temperature applications. The technology research and development ongoing at NASA Glenn Research Center for applications to future launch vehicles, space vehicles, and ground systems is outlined.

I. Introduction

To create the technologies, knowledge, and infrastructures for long duration, more distant human and robotic missions for the Vision for Space Exploration and to enable safer, lighter, quieter, and more fuel efficient intelligent vehicles for NASA's aeronautics mission, instrumentation technologies are being developed by NASA Glenn Research Center (GRC). The Sensors and Electronics Branch at NASA GRC has an in-house effort to develop thin film sensors for surface measurement in propulsion system research. The sensors include those for strain, temperature, heat flux and surface flow which will enable critical vehicle health monitoring of future space and air vehicles (refs. 1 and 2).

The use of sensors made of thin films has several advantages over wire or foil sensors. Thin film sensors do not require special machining of the components on which they are mounted, and, with thicknesses less than 10 μm , they are considerably thinner than wire or foils. Thin film sensors are thus much less disturbing to the operating environment, and have a minimal impact on the physical characteristics of the supporting components.

A range of thin film sensor technology has been demonstrated enabling measurement of multiple parameters either individually or in sensor arrays including temperature, strain, heat flux, and flow. Multiple techniques exist for refractory thin film fabrication, fabrication and integration on complex surfaces, and multilayered thin film insulation. The current challenges of thin film sensor technology are to (1) develop specialized sensor systems and (2) develop instrumentation techniques for higher temperature applications exceeding 1000 $^{\circ}\text{C}$ and for application on components with complex surfaces. This paper is a review of the thin film sensor research and development ongoing at NASA GRC for applications to future launch vehicles, space vehicles, and ground systems.

II. Development of Specialized Sensors

A. High Temperature Strain Sensor Technology

NASA GRC has lead the development and application of high temperature strain sensors based on an alloy of palladium and chromium (PdCr). PdCr thin film strain gauges have been demonstrated in an air furnace up to 1100 $^{\circ}\text{C}$ and in a heat flux calibrator with heating rates up to 1100 $^{\circ}\text{C}/\text{sec}$ and heat flux up to 2 MW/m^2 . The dynamic gauges were also fabricated on an advanced silicon nitride turbine blade shown in figure 1, and survived tests up to 42,500 rpm and fatigue tests at $\pm 2000 \mu\text{e}$ up to 1000 $^{\circ}\text{C}$ for a million

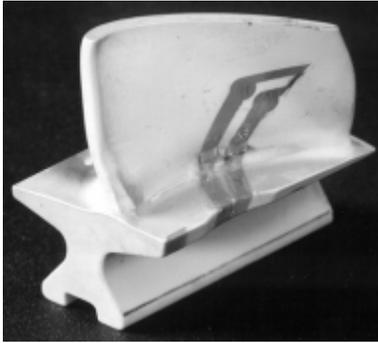


Figure 1.—PdCr thin film strain gauge applied on a ceramic turbine blade.



Figure 2.—Rendering of a conceptual thin film strain gauge on cervical implant plate.

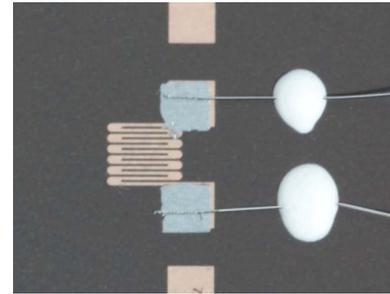


Figure 3.—Thin film strain gauge for durability testing on TiAl alloy sample.

cycles. The gauges have also been demonstrated on SiC/SiC ceramic matrix composite components in a jet-fueled burner rig operating at surface temperatures of approximately 1100 °C.

The apparent strain of a PdCr dynamic strain gauge is stable and repeatable between thermal cycles to 1100 °C when connected to a Wheatstone bridge circuit in a quarter bridge configuration (ref. 3) The apparent strain sensitivity is approximately 85 $\mu\epsilon/^\circ\text{C}$ which is less than the permissible value of 100 $\mu\epsilon/^\circ\text{C}$ for dynamic strain gauges (ref. 4) and the drift strain at 1100 °C is less than the permissible value of 500 $\mu\epsilon/\text{hour}$. The resulting apparent strain characteristic of a PdCr static strain gauge connected to a Wheatstone bridge circuit in a half bridge configuration is stable and repeatable to within $\pm 200 \mu\epsilon$ between thermal cycles to 1100 °C with a sensitivity less than 3.5 $\mu\epsilon/^\circ\text{C}$ in the entire temperature range. The apparent strain of the PdCr compensated thin film gauge can be corrected to within $\pm 200 \mu\epsilon$ if the temperature measurement uncertainty is within 57 °C. The gauge is stable and responds linearly to mechanical loads up to 1050 °C. This is over 300 °C above the usable temperature for conventional NiCr strain gage technology. The strain sensitivity, or gauge factor, for PdCr decreases approximately 22 percent from room temperature to 1050 °C.

A weldable PdCr thin film strain gauge was developed for applications that do not allow a gauge to be sputtered directly on to the component because the component is too large to be accommodated in the deposition rig or when gauge installation must be performed in the test field. The gauge is first deposited on a metal shim that has a similar coefficient of thermal expansion to that of the substrate material. The shim is then welded onto the test article. The mechanical response of the weldable gauge is similar to that of a direct-deposited gauge in that it is linear to the mechanical load and does not cause delay in strain transfer (ref. 3).

A Bio-MEMS concept utilizing NASA GRC's thin film technology that is being examined with the Cleveland Clinic Learner Research Institute (Cleveland, Ohio) is for the application of thin film strain gauges as embedded cervical plate instrumentation for spinal implants. A concept rendering is shown in figure 2. A test gauge of platinum was deposited on a sample of the titanium-aluminum alloy used in the implants as shown in figure 3, and the performance of the gauge was examined after at least 60 days of immersion in a saline bath. The gauge held up quite well and did not delaminate under these conditions. Future tests are being discussed.

B. Thin Film Thermocouples

Thin film thermocouple development at NASA GRC has concentrated on the application of platinum-13 percent rhodium versus platinum (ANSI Type R) thermocouples due to their simple composition and high temperature capability. Thin film thermocouples have been fabricated and tested on a number of substrate systems including nickel-based superalloys, silicon carbide, silicon nitride, mullite and aluminum oxide ceramics, ceramic matrix composites (CMC) and intermetallics. The sensors have been demonstrated on various test component configurations and in different test environments (ref. 2).

Thin film thermocouples were demonstrated on Space Shuttle Main Engine (SSME) turbo pump blades (fig. 4) in a test facility designed to simulate the highly transient temperature and pressure



Figure 4.—SSME turbo pump blade with thin film thermocouples.

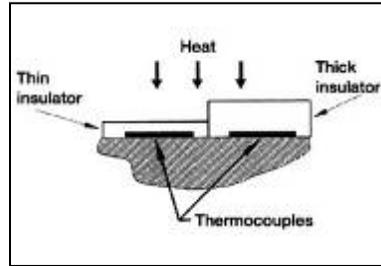


Figure 5.—Schematic of heat flux measurement.



Figure 6.—Thermopile heat flux sensor.



Figure 7.—Heat flux sensor utilizing a resistance bridge.

conditions of the SSME high pressure fuel turbo pump environment. The blades were nickel-based superalloys as were a series of flat substrates instrumented with thin film thermocouples and tested in hydrogen-fueled burner rigs. The films proved to be highly adherent and durable to the 1000 °C test conditions (ref. 5).

Several SiC fiber/SiC matrix ceramic matrix composite (CMC) panels, cylinders, and combustor liners have also been instrumented with thin film thermocouples and successfully tested in a combustor test facility to meet propulsion capability goals of several development programs (refs. 1 and 6). A hydridopolysilazane fiber/silicon carbide matrix CMC liner was tested with thin film thermocouples in a jet-fueled burner rig operating under pressures of 0.7 to 2 MPa and gas temperatures of 1500 °C. Temperature data up to 1100 °C was obtained for over 25 hr. of testing. The typical initial failure mode for the sensors is the detachment of the lead wires from the sensor film (ref. 6).

C. Heat Flux Sensors

There are various designs of heat flux sensors, such as Gardon gauges, plug gauges, and thin film thermocouple arrays (refs. 7 to 9). The thin film types have the advantage of high frequency response and minimal flow disturbance (ref. 10). All heat flux sensors operate by measuring the temperature difference across a thermal resistance, as shown in figure 5. The signal level of these sensors are low, typically a few millivolts for a Watt per square centimeter of heat flux.

A thin film heat flux sensor developed at NASA GRC is fabricated as a thermocouple array on the surface of a ceramic material. Because of the small temperature differences involved, and the small output of a single junction, the thermocouples are arranged as a thermopile (fig. 6). A thin film of a thermal barrier coating (TBC) such as silicon oxide or yttria-stabilized zirconia is sputtered over the pairs in the center of the array to form the cold sink. The thin film thermopile heat flux sensors were demonstrated in an arc-lamp calibration facility that could produce repeatable heat flux of 0.02 to 5 MW/m² with temperatures on the surface of the sensors of up to 800 °C. It was found that a 40-pair Type R thermocouple thin-film heat flux gauge has sensitivity of 1.2 μV/(W/cm²) and a dynamic frequency response of 3 kHz (ref. 10).

A new design for a thin film heat flux sensor utilizing a resistance bridge, shown in figure 7, was developed at NASA GRC. The temperature difference from the heat flux through different thicknesses of

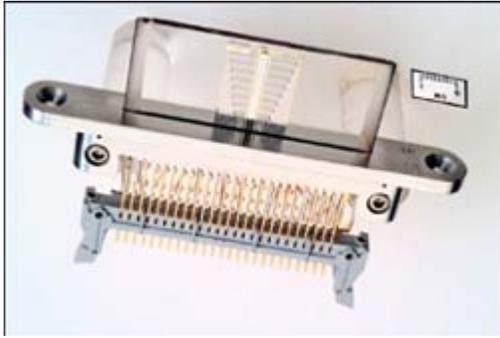


Figure 8.—The thermocouple boundary layer rake.

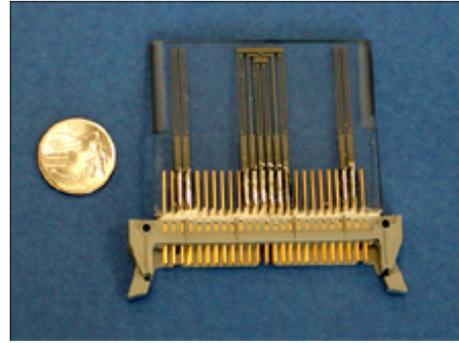


Figure 9.—Thin film air mass flow sensor prototype.

thermal insulation is measured by thin film RTD's instead of a thermopile. The result is a sensor design that has a larger signal of $3 \text{ mV}/(\text{W}/\text{cm}^2)$ and is more easily scalable than the thermopile designs (ref. 11).

D. Thin Film Flow Sensors

Conventional flow-measuring devices that can measure the flow velocity within the boundary layer all have the limitation that measurements cannot be made very close to the surface. The patented thermocouple boundary layer rake shown in figure 8 detects the flow by using a thin-film thermocouple array to measure the temperature difference across a heater strip (ref. 12). The heater and thermocouple arrays are microfabricated on a constant thickness quartz strut with low heat conductivity. The device can measure the velocity profile well into the boundary layer, about $65 \text{ }\mu\text{m}$ from the surface, which is almost four times closer to the surface than has been possible with the previously used total pressure tube (ref. 13).

NASA GRC also has patented a new air mass flow sensor design used to provide accurate information about the amount of air entering an engine so that the amount of fuel can be adjusted to give the most efficient combustion (ref. 14). The design consists of thin film resistance temperature detectors (RTD's) in a resistor bridge arrangement, as shown in figure 9. To minimize disturbance to the airflow being measured, the RTD's are fabricated on a thin, constant-thickness airfoil. Compared to other air mass flow sensor designs, the thin film sensor is much more robust than hot wires, less disturbing to the airflow than pitot tubes, more accurate than vane anemometers and simpler to operate than thermocouple rakes to determine bulk air mass flow.

E. Multi-Functional Sensor System

The patented thin film multifunctional sensor developed at NASA GRC integrates into one "smart" sensor the designs of individual gauges that measure strain magnitudes and direction, heat flux, surface temperature, flow speed and direction (refs. 15 and 16) The entire gauge is microfabricated, enclosing a triangular area approximately 1.5 cm on a side with $50\text{-}\mu\text{m}$ -wide features. Designed for applications in material systems and engine components testing, the sensor can provide minimally intrusive characterization of advanced propulsion materials and components in hostile, high-temperature environments, validation of propulsion system design codes, and experimental verification of computational models.

Integrating NASA GRC thin-film sensor technology into a single gauge for simultaneous measurement of surface temperature, strain, and heat flux is the first step toward smart sensors with integrated signal conditioning and the capability to provide feed back to an operating system in real time. Various prototypes of the gauge have been bench-tested on alumina substrates (ref. 16), and are shown in figures 10 and 11. Future testing will include measuring all of the parameters simultaneously on an engine component to be tested in the lab as well as in harsh environments.



Figure 10.—A thin film multifunctional sensor with an off-axis strain rosette and a Type R thermopile heat flux sensor.



Figure 11.—A thin-film multifunctional sensor with an on-axis strain rosette and a Type R thermocouple.

Alternate materials for the sensor elements will be explored for use in higher temperature applications. As discussed later in this paper, ceramic materials are being investigated to replace the metals currently being used. An electronics package will be developed to allow the sensor to become “smart”. Additionally, the sensor is to be developed as a transferable gauge, similar to a weldable strain gauge.

III. Development of Instrumentation Techniques

A. Capabilities and Facilities

NASA GRC is a leader in instrumentation and sensor R&D for harsh conditions with existing long-term programs in Optical Instrumentation, NDE, Intelligent Controls and Microsystems that have contributed NASA GRC technology to many programs across NASA and industry. The MEMS thin film sensors fabrication facilities contain an available 1000 square foot Class 1000 clean room facility and a 1000 square foot Class 100 facility with a variety of deposition equipment and photolithography facilities. Portions of the facility are shown in figure 12. Sensors and devices are characterized in-house using a range of facilities and techniques, including scanning electron microscopy and Auger electron spectroscopy.

The fabrication equipment for thin film micro-instrumentation includes several physical vapor deposition systems with high temperature capability, mask aligners for photolithography, wet chemical stations and a surface profilometer. The fabrication and testing of sensors in thin film form have been demonstrated on several materials and components for jet aircraft and space-based engine applications, including superalloys, ceramics, intermetallics, and ceramic matrix composite materials. They have been tested in laboratory furnaces tests as well as in harsh environments, including gas turbine and hydrogen/oxygen engine environments under both low and high pressure conditions, a high heat flux facility and a diesel engine environment.



Figure 12.—The GRC Microsystems Fabrication Clean Room Facility is specifically designed to support the fabrication and evaluation of thin film prototype devices for high temperature applications.

Thin film layers are fabricated with physical vapor deposition methods (sputter deposition, e-beam vapor deposition) directly on the components, and the sensors are patterned by photolithography methods and/or stencil masks. Typical deposited films are up to 5 μm thick with line widths down to 25 μm , and are custom tailored for the specific application requirements. A listing of refractory materials currently in use for producing thin film layers is given in table 1.

TABLE 1.—REFRACTORY THIN FILM MATERIAL CAPABILITY AT NASA GRC

Thin film	Uses
Aluminum Oxide (AlOx)	Electrical and Thermal Insulation
Chromium (Cr)	General Coatings
Chromium Silicide (CrSi)	Temperature Sensors
Indium Tin Oxide (ITO)	Strain Gauges, General Coatings
Molybdenum (Mo)	General Coatings
Palladium and Palladium Alloys (Pd-)	Strain Gauges, Radiation Detectors, General Coatings
Platinum and Platinum Alloys (Pt-)	Strain Gauges, Heat Flux Gauges, Temperature Sensors, Flow Sensors
Silicon Oxide (SiOx)	Electrical and Thermal Insulation
Tantalum (Ta)	Strain Gauges
Titanium (Ti)	General Coatings
Tungsten (W)	General Coatings
Ytria-Stabilized Hafnia (YSH)	Thermal Insulation
Ytria-Stabilized Zirconia (YSZ)	Thermal Insulation

B. 3D Fabrication Techniques

A particular challenge that is being examined at NASA GRC is the deposition and patterning of thin film sensors on curved and/or complex surfaces. The most straightforward method is to fabricate metal shadow masks with the pattern cut into them, and then wrap them around the component. For complex shapes, such as small turbine blades, castings can be made of the components for fabricating the metal masks for the sensors. Sensors from shadow mask patterns are appropriate for large feature sensors and

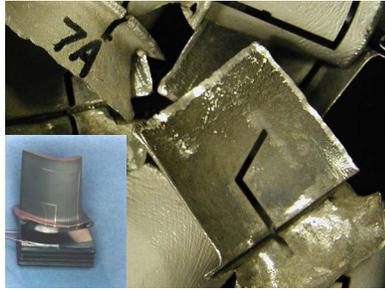


Figure 13.—The metal shadow masks used to fabricate thermocouples on a SSME turbo pump blade (inset).



Figure 14.—Thin film strain gauge patterned on an engine valve using flexible photo-masks.

minimize the component exposure to etching chemicals. An example of this application is the SSME turbine pump blade (ref. 5) shown with the masks in figure 13.

Flexible plastic film masks can allow fine-lined sensor patterns to be fabricated using standard lift-off processes, and currently is our standard method of fabricating sensors on complex surfaces. An example of the capability is shown in figure 14. The use of laser trimming equipment is being examined to cut fine-line features on components covered with thin sputtered films, but the focal field of the laser limits the allowed curvature of the components.

C. Multi-Layered Thin Film Insulation

Fabricating metal sensors directly on metal components requires the use of an electrically insulating layer between the component and the sensor. Flame-sprayed insulators provide good insulating capability, but the thickness of the coatings (300 μm and greater due to the coating porosity) lessens the advantage of the low-profile thin film sensor. NASA GRC has been examining the use of thin film insulators as an alternative. The use of thin films to electrically insulate thin film sensors on engine components minimizes the intrusiveness of the sensors and allows a more accurate measurement of the environment. One process developed utilizes a 125 μm thick NiCoCrAlY base coat on which alumina can be thermally grown and vapor-deposited (ref. 17).

To further this research, NASA GRC and Rolls-Royce (Derby, United Kingdom) pursued a joint investigation using multilayered thin film dielectrics as a reliable insulator in harsh environments (ref. 18). A major cause of conduction in thin film dielectrics is the presence of defects, such as pinholes, that propagate through the film to the underlying substrate surface. By alternating the insulating material, each new growth pattern would deviate from the previous one, eliminating direct pathways for conduction to the substrate.

The insulating properties of test samples using multilayered insulators of alumina and either yttria-stabilized zirconia (YSZ) or chromium carbide (CrC) overcoated with a sputtered top layer of alumina were tested in a high-temperature air oven to determine their suitability. An example of a test sample is shown in figure 15. Each multilayered insulator sample was 5 μm thick, at least an order of magnitude thinner than conventional insulators, and showed a stabilized film at temperatures in excess of 800 $^{\circ}\text{C}$. The application of the YSZ-alumina insulator has been demonstrated on a nickel-alloy fan blade, as shown in figure 16.

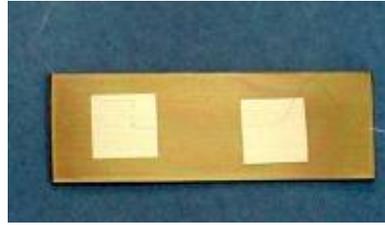


Figure 15.—YSZ-alumina multilayer on a metal substrate for testing.



Figure 16.—YSZ-alumina multilayer insulating a resistance temperature detector on a nickel-alloy fan blade.

D. Future Directions: Thin Film Ceramic Sensors

The need to consider ceramic sensing elements is brought about by the temperature limits of metal thin film sensors in propulsion system applications. The capability for thin film sensors to operate in 1500 °C environments for 25 hr or more is considered critical for ceramic turbine engine development (refs. 19 and 20). For future space transportation vehicles, temperatures of propulsion system components of at least 1650 to 3000 °C are expected (ref. 21).

Ceramic materials can survive extreme temperatures. The borides, carbides, nitrides, and silicides of metals as well as conducting oxides show high heat-resisting properties as well as metal-like electrical properties that make them attractive for use as sensing elements at high temperatures. NASA GRC with Case Western Reserve University (CWRU) and the University of Rhode Island (URI) are investigating the feasibility of using ceramics as thin-film thermocouples for extremely high temperature applications, thus taking advantage of both the stability and robustness of ceramics and the non-intrusiveness of thin films (ref. 22).

Thermocouple samples for testing were fabricated at NASA GRC from high-purity sputtering targets from CWRU. Thermoelectric data on thin-film chromium silicide (CrSi) and tantalum carbide (TaC) were measured for temperatures up to 650 °C for CrSi and to 450 °C for TaC. The thermoelectric voltage output of a thin-film CrSi versus TaC thermocouple was found to be at least 10 times that of the standard type R (platinum-rhodium vs. platinum) thermocouple, producing 59 mV with a 600 °C temperature gradient. Figure 17 shows the CrSi-TaC thermocouple in a test fixture at NASA GRC, and the resulting output signal is compared with a type R thermocouple output in the figure 18. NASA GRC has also teamed with the Thin Films and Interfacial Research Center of URI in ceramic-based thermocouple research (ref. 23). The initial results are of two thin-film indium-tin-oxide (ITO)-based thermocouples fabricated and tested at URI. The thermoelectric voltage outputs are consistently similar to that of type R thermocouples when cycled to 1500 °C. Figure 19 shows the ITO thermocouple being tested at URI.



Figure 17.—Test fixture in GRC's Thin Film Sensors Laboratory with the CrSi-TaC test sample in place.

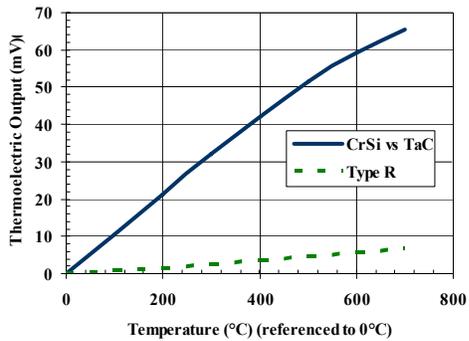


Figure 18.—Relative thermoelectric voltage output of the CrSi-TaC thermocouple compared with the standard type R thermocouple.

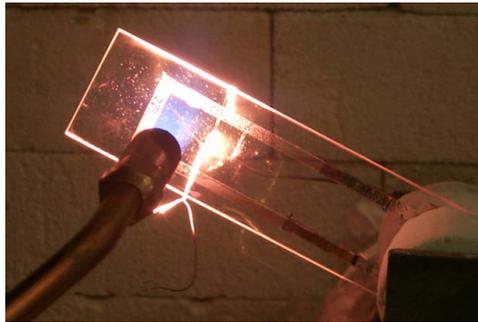


Figure 19.—ITO ceramic thermocouple fabricated and tested at the University of Rhode Island.

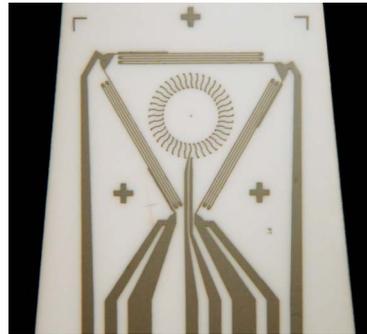


Figure 20.—A Multifunctional Rosette Sensor fabricated from Tantalum Nitride at NASA GRC.

A microfabricated ceramic multifunctional sensor rosette for operation at extreme temperature conditions is under development at NASA GRC. A prototype is shown in figure 20. The high temperature stability and low thermal coefficient of resistivity (TCR) of tantalum nitride makes it possible for a multifunctional sensor to be used as a static strain sensor with little or no temperature compensation and with the capability of applications to extremely high temperatures. Preliminary tests indicate that the thin film ceramic multi-functional sensor has strain and temperature sensitivities comparable to noble-metal alloys used for high temperature applications. Optimization of the ceramic film is underway to achieve a stable sensor for measuring static characteristics at extremely high temperatures.

This merging of the high-temperature capabilities of ceramics with the non-intrusiveness of thin films is ongoing. It appears that a new class of ceramic thin films can be used as high-temperature thermocouples, resistive temperature and strain sensors. This research advances the effort to develop a complete sensor package using ceramics as thin-film sensors in environments where standard metal sensors would not survive.

IV. Summary

In order to achieve the advanced engines in the future, knowledge of the physical parameters of the engine and engine components is necessary both on the test stand and in flight. NASA GRC has a history of being a world-leading pioneer in the development and application of thin film, embedded sensor technology for aeronautic engine applications and extreme environments. The technologies have applications to future launch vehicles, space vehicles, and ground systems. A range of sensor technology has been demonstrated enabling measurement of multiple parameters either individually or in sensor arrays

including temperature, strain, heat flux, and flow. Multiple techniques exist for refractory thin film fabrication, fabrication and integration on complex surfaces, and multilayered thin film insulation. Leveraging expertise in thin films and high temperature materials, investigations for the applications of thin film ceramic sensors has begun. The current challenges of instrumentation technology are to further develop systems packaging and component testing of specialized sensors, further develop instrumentation techniques on complex surfaces, improve sensor durability, and to address needs for extreme temperature applications.

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REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 2006	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Thin Film Physical Sensor Instrumentation Research and Development at NASA Glenn Research Center			5. FUNDING NUMBERS WBS 561581.02.01.03.08	
6. AUTHOR(S) John D. Wrbanek and Gustave C. Fralick				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-15674	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2006-214395	
11. SUPPLEMENTARY NOTES Prepared for the 52nd International Instrumentation Symposium cosponsored by the ISA Aerospace, Test Measurement and Process Measurement and Control Divisions, Cleveland, Ohio, May 7-11, 2006. Responsible person, John D. Wrbanek, organization code RIS, 216-433-2077.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 35 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A range of thin film sensor technology has been demonstrated enabling measurement of multiple parameters either individually or in sensor arrays including temperature, strain, heat flux, and flow. Multiple techniques exist for refractory thin film fabrication, fabrication and integration on complex surfaces and multilayered thin film insulation. Leveraging expertise in thin films and high temperature materials, investigations for the applications of thin film ceramic sensors has begun. The current challenges of instrumentation technology are to further develop systems packaging and component testing of specialized sensors, further develop instrumentation techniques on complex surfaces, improve sensor durability, and to address needs for extreme temperature applications. The technology research and development ongoing at NASA Glenn for applications to future launch vehicles, space vehicles, and ground systems is outlined.				
14. SUBJECT TERMS Thin films; Sensor; High temperature; Ceramics; Thermocouples; Heat flux; Strain gages			15. NUMBER OF PAGES 17	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

